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ABSTRACT

This report details the stages in the development of a novel oxygen system pipe cleaning system, and associated cleaning procedures, for use at RAAF oxygen maintenance workshops. This cleaning system uses 3M HFE solvents and pressure vessels for solvent delivery. Detailed test results and procedures are included. These tests covered RAAF oxygen system pipes in various diameters ranging from 1/8" to 1/2" in stainless steel, copper and aluminium, and various pipe connectors. The tests showed that the final system developed is able to meet the RAAF cleanliness specification for oxygen systems for both non-volatile residue and particulate contamination.

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Executive Summary

Dry breathing oxygen is extensively used in RAAF aircraft to provide oxygen to pilots in non-pressurised cabins and as an emergency supply in all other fixed wing aircraft. Oxygen is a strong oxidiser and does pose a substantial fire hazard in aircraft. To manage this risk, the pipes and components used in oxygen system must be cleaned to rigorous cleanliness specifications. Historically CFC-113 was used to clean oxygen systems, but with the ban on chlorofluorocarbons (CFCs), due to the ozone depleting properties of CFCs, new cleaning methods were required.

As part of the RAAF Oxygen System Replacement Project, DSTO was asked to assist Aircraft Maintenance Processes Technologies and Standards (AMPTS) develop and trial a pipe cleaning system. The cleaning system that was developed was a multi-stage process, fully incorporated into one transportable cleaning unit.

The stages can be summarised as follows:

1. Initial degrease and particulate removal with recirculating HFE-71DE solvent. HFE-71DE has good solvent properties, but is not fully compatible with high-pressure oxygen.
2. Further degrease and particulate removal with recirculating HFE-7100 solvent. HFE-7100 has poor solvent properties, but is fully compatible with oxygen.
3. A final rinse with unused HFE-7100 to ensure complete oxygen compatibility.
4. A drying stage using high purity nitrogen gas.

Results of tests with RAAF oxygen system pipes in the size range 1/8 inch to ½ inch, in stainless steel, copper and aluminium showed that the above cleaning system meets RAAF oxygen system cleanliness specifications for both non-volatile residue and particulate contamination.

The recommended final cleaning procedures comprises a five minute flush in both directions for both HFE-71DE and HFE-7100 at flowrates above the onset of turbulence, calculated using a Reynolds Number of 4000; followed by a final rinse with 600 ml of clean HFE-7100 at one litre/min. The pipes were dried with high purity nitrogen until a refrigerant leak detector no longer signalled the presence of any HFE solvents.

Authors

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Lyn Fletcher, BAppSc in Chemisry (RMIT), MEnvSc (Monash University) joined DSTO in 1984. Lyn started at DSTO investigating the affects of solvents on polymeric materials. In 1987 she began undertaking research into waste management and environmental protection for the RAN. As part of this work she became involved in CFC and Halon replacement for the RAAF and the RAN. She currently leads the team undertaking research on oxygen system pipe and component cleaning.

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Robert Zugno, Cert. App Sci., Footscray TAFE, joined DSTO in 1977. Robert has been involved with fuel, lubricant and elastomer investigations. Since 2000 he has been assisting a team researching oxygen system pipe and component cleaning.

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Jim Dimas, Cert. Surface Tech. (VUT), AssocDipAppSc (NMIT), BAppSc (RMIT), joined DSTO in 1987. Jim started at DSTO as a trainee technical officer and after completing the trainee program he was permanently attached as a technical officer to the light armour research area in 1990. In 2000 as a professional officer he transferred to the navy environmental research area, he also works with the team researching oxygen system pipe and component cleaning.

Contents

1. Introduction

Aircraft in the Royal Australian Air Force (RAAF) have dry breathing oxygen (DBO) installed in aircraft without pressurised cabins and as an emergency supply in case of accidents involving fire and smoke, or loss of cabin pressure. Oxygen can be supplied in high-pressure gas cylinders or as liquid oxygen. This oxygen is then distributed throughout the aircraft to crew and passengers in a series of pipelines that must be cleaned to stringent cleanliness standards.

Oxygen is a highly reactive product and its use in aircraft is not without some risk [1]. It is a strong oxidiser that vigorously supports combustion. To manage the risk that 100% oxygen poses, care must be taken to eliminate the two other requirements for combustion, namely possible fuels and ignition sources. In oxygen system design, care is given to material compatibility with oxygen. Therefore, the thorough cleaning of oxygen systems is of prime importance to ensure the absence of possible fuels and ignition sources. For this reason oxygen systems are cleaned to rigorous standards to ensure flammable contaminants are removed and that no particles remain that have enough mass to release sufficient energy during a high velocity impact to initiate ignition. Non-volatile residue (NVR) is the parameter to measure the level of combustible contaminants and a particle limit is specified to manage impact ignition risks. Particles can have a higher risk if they consist of combustible material.

The RAAF currently work to a cleanliness specification based on ASTM G93 "Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment Used in Oxygen-Enriched Environments" of 33 mg/m^2 (3 mg/sqft) for surface NVR and a modified ASTM G 93 175 for particle specification [2]. The RAAF has modified the ASTM G 93 175 particle specification to allow unlimited particles below 50 microns instead of the 20 particles between 5 and 50 microns, provided the particles do not silt, or the weight of the particles do not cause the NVR specification to be exceeded.

This was done because the ASTM G 93 175 specification is very tight in the lower particle size range and experience has shown that there are often more than 20 particles in the 5 to 25 microns range. These particles pose less risk for oxygen systems and other standards, such as SAE ARP1176 "Aerospace Recommended Practice - Oxygen System and Component Cleaning and Packing" [3] and Mil-STD-1246C "Product Cleanliness Levels and Contamination Control Program,"[4] all specify a higher particle size limit below which the number of particles is unlimited for a comparable cleanliness level.

The current RAAF specification allows unlimited particles below 50 microns, no more than 5 particles between 50 and 100 microns, one particle between 100 and 175 microns and no particles greater than 175 microns, per 0.09 m^2 (1 sqft) of surface area flushed with 100 mL of solvent.

As a result of the Montreal Protocol ban on CFC production and use, the RAAF has adopted a two-stage cleaning process using 3M™ HFE solvents to replace CFC-113 for cleaning of the pipes and metallic sub-assemblies in oxygen systems. The two-stage process relies on 3M HFE-71DE for degreasing, followed by a final clean with 3M HFE-7100. This two-stage process was adopted because an initial study into CFC-113 replacements failed to identify a single non-toxic, replacement solvent that was fully oxygen compatible and had good cleaning performance [5]. Oxygen compatibility is identified as a pass in both the autogenous ignition temperature (bomb) test and impact ignition in oxygen enriched environments.

The solvents chosen for the RAAF oxygen system component and pipe cleaning are HFE-71DE and HFE-7100. HFE-71DE is an azeotropic mixture of methoxy-nonafluorobutane and trans-1,2-dichloroethylene. HFE-7100 is pure methoxy-nonafluorobutane. HFE-7100 is fully compatible with oxygen, but has only fair degreasing ability. The addition of trans-1,2-dichloroethylene to HFE-7100 greatly improves the degreasing ability of HFE-71DE, but the addition of trans-1,2-dichlorethylene adds some non-volatile stabilisers to the solvent that renders HFE-71DE not fully compatible with high pressure oxygen. Consequently to ensure good degreasing and full oxygen compatibility both solvents are required: HFE-71DE initially as a degreaser, followed by HFE-7100 to remove any residue of HFE-71DE [5].

The RAAF, together with DSTO, have subsequently developed a pipe cleaning rig that flushes these solvents through at turbulent flow to effectively wet, suspend and remove particulate and NVR contamination from pipes.

To achieve this, and use the least volume of HFE solvents, the initial clean was performed using previously used solvent in a recirculating process after inline filtration. In this way filtered solvent can be used to remove particulates, and most non-volatile residue. A final flush with clean HFE-7100 ensures all non-volatile residue from previous solvents is removed.

This paper details the evolution in the design and principles of the pipe cleaning equipment and the results of pipe cleaning tests.

2. Methodology

2.1 Pipe Cleaning Rig Descriptions and Associated Cleaning Methods

During development of the pipe flushing equipment and procedures, three different rigs were set-up and tested, with each subsequent design becoming more compact and self-contained. However, they were all capable of delivering the solvent at the appropriate flow-rates and worked on the same principles. Therefore, considering it is the flow rates of solvents and the duration that are the important determinants in the overall cleaning process, testing done on the different cleaning rigs can be compared directly.

The first design was a simple laboratory mock-up (proof-of-concept rig) that was used to confirm the proposed pipe-cleaning concept with pressure vessels. The second was manufactured by Rosebank engineering (pre-production rig) and consisted of a recirculating module and final flush module. The final rig (the production rig) included both modules in one stand-alone unit that can be readily packed and transported between workshops.

2.1.1 Principal of RAAF Pipe Cleaning Rigs

Initial investigation by DSTO developed the underlying principals required for pipe cleaning. The RAAF cleaning specification calls for two conditions to be met. First the particle contamination must be below the ASTM G93, 175 micron specification for particles greater than 50 micron and below the SAE 1176, level 200 specification, for particles less than 50 micron. Second the non-volatile residue must be below 3 mg/sqft.

To achieve the required cleanliness a number of conditions must be achieved. Particles have to be suspended and remain in suspension until they are removed from the pipes and for NVR the solvent must be able to dissolve or suspend the chemical and this process can take time. In order to remove surface particulate contamination a source of energy (such as turbulence) is required at the pipe wall and solvent interface. There are a number of ways to achieve this, but the easiest is to ensure that turbulent flow is obtained. A flowrate above a Reynolds number of 4000 was recommended to achieve turbulence. To ensure time for the HFE solvents to dissolve the NVR a contact time of 6-15 minutes for solvent degreasers was recommended as a minimum.

The most economical way of achieving this was to use a recirculating system. However, to ensure sufficient NVR removal and to ensure full oxygen compatibility, a final rinse with HFE-7100 was included. Three options were considered for solvent delivery. The first was by pump, the second was using pressure vessels and the third was by using vacuum. Experience with pumps in other cleaning equipment being tested in this laboratory has shown that the HFE-71DE can be incompatible with many

common pump materials and sourcing a robust pump may be difficult [unpublished reports - Lyn Fletcher]. Vacuum systems would consume much more solvent due to the high vapour pressure of the solvents chosen. It was decided to investigate whether a system based on a series of pressure vessels would be feasible as it would remove the possibility of pump failure and cross contamination of HFE-7100 and HFE-71DE.

A preliminary cleaning method was developed and refined during subsequent tests. However, one important difference with using the pressure vessels compared to pumps is that it is not possible to preset a flowrate. What must be known before cleaning starts is what pressure to use in the delivery vessel to deliver the required flowrate. The recirculating time, pressures and flowrates used are discussed in more detail in the later sections. However, the basic requirements were for 5 - 15 minutes of flushing with HFE-71DE through the attached pipes in both directions as the primary degreasing step, followed by 5-15 minutes flush with HFE-7100 for 5 - 15 minutes to remove particulates and any residue left by the HFE-71DE, finally followed by 1 litre flush of unused HFE-7100 to ensure that all NVR is removed.

In addition, to improve particulate removal efficiency by reducing as much as practical any uphill configuration, the pipes were positioned on the recirculating rigs to be as horizontal as possible. For the final flush, where flow direction is only in one direction, the pipes were angled downwards to get gravity assistance with final particle removal.

2.1.2 1/4" Proof of Concept Rig

The proof of concept rig was a laboratory mock up of a solvent delivery system using pressure vessels pressurised with nitrogen gas. The pressure is then used to dispense the solvents through the pipes at the required flowrate. The pressure to achieve the desired flowrate is a function of the backpressure through the pipes and other associated valves, filters and fittings.

The proof of concept rig was kept simple and consisted of pressure vessel, on-off valves, and 2-micron inline filters to which the pipes were connected. Another pressure vessel was added to the end of the test pipes to collect the solvent. To recirculate the solvent the receiving and delivery pressure vessels were swapped over and the process repeated. Two vessels were used for the HFE-71DE recirculation, 2 vessels for the HFE-7100 recirculation, and one for the HFE-7100 final rinse using clean HFE-7100 solvent.

These initial tests with the proof of concept rig were used to determine the requirements for non-volatile residue removal. Ten times the internal volume of the pipes plus 100 ml was used for the 1/4" pipes. This equated to 600 ml of HFE-71DE. The HFE-7100 was used in greater amounts and 10 litres were flushed through in one direction only. The flowrate for these tests was generally 2 l/min for the 1/4" pipes. For the final flush with clean HFE-7100, 600 ml was delivered to the test pipes at a flowrate between 0.5 and 1 l/min.

2.1.3 3/8" Pre-production Rig

The pre-production rig (PPRig) consisted of two modules, manufactured by Rosebank Engineering to a RAAF/DSTO design. The first module, the reverse cycle rig, was designed to recirculate HFE-71DE and HFE-7100 from pressurized containers and be capable of reversing the flow direction through the pipes. Figure 1 shows a schematic of the reverse cycle rig.

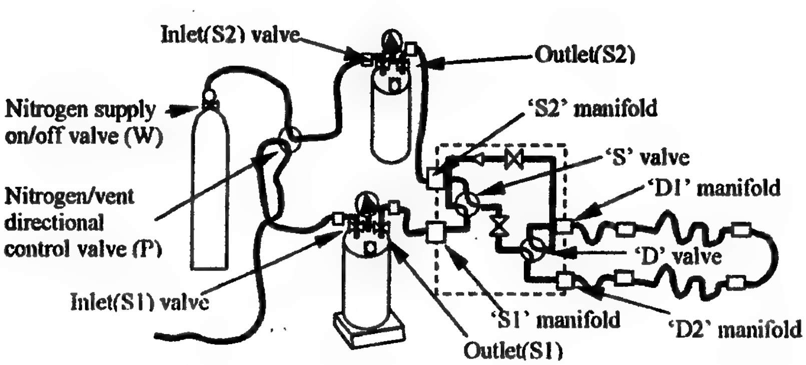

Figure 1 - Reverse Cycle Rig.

The second module was designed to provide new HFE-7100 solvent through the pipes as a final flush and simplified verification step. Figure 2 shows the schematic of the final flush rig.

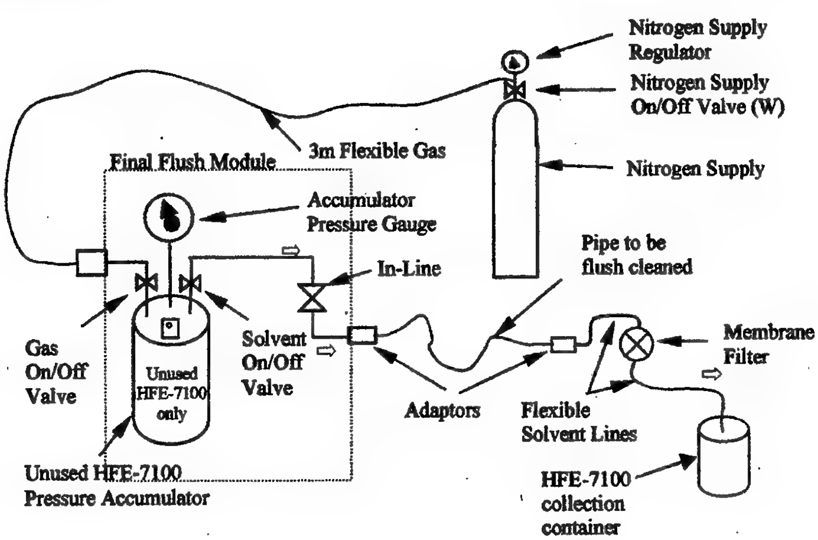

Figure 2 - Final Flush Rig.

The pre-production rig was used to develop the overall cleaning instructions that would be given to the workshops [6]. As such, the time used for recirculating fluids was altered in the various trials and the delivery pressure and subsequent solvent flow rates was altered to enable comparisons. These are documented in the results section for each pipe tested.

The final conditions recommended were 5 minutes in each direction for both HFE-71DE and HFE-7100 recirculating solvents. The flowrates used for each of the pipes tested are discussed in detail in Section 4.1.

Between change over of solvents the pipes were purged for 2 minutes at 100 KPa with high purity nitrogen, delivered through the last pressure vessel connected. The final rinse was 600 ml of clean HFE-7100 flushed through at approximately 0.6 l/min. The pipes were then dried with high purity nitrogen until a refrigerant leak detector stopped alarming when waved over the end of a dried pipe.

2.1.4 3/8" Production Rig

The final design of the production rig involved merging the recirculating rig and the final rinse rigs. The Final Production Rig has a trolley with underneath storage for all of the pressure vessels and associated fittings. The production rig has two in-line flow meters that can measure flow rates directly, allowing for finer adjustment of the flowrates. Careful consideration was given to the venting requirements and a dedicated vest line was included. The full schematic of the rig is shown in Figure 3 and Figure 4 illustrates the rig in operation.

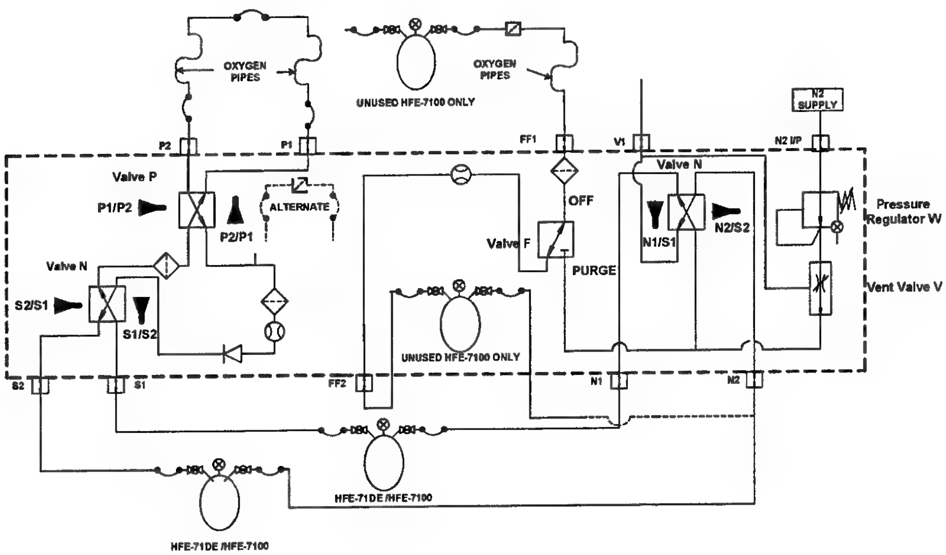

Figure 3 - Schematic of the Final Production Model of the Pipe Cleaning Rig.

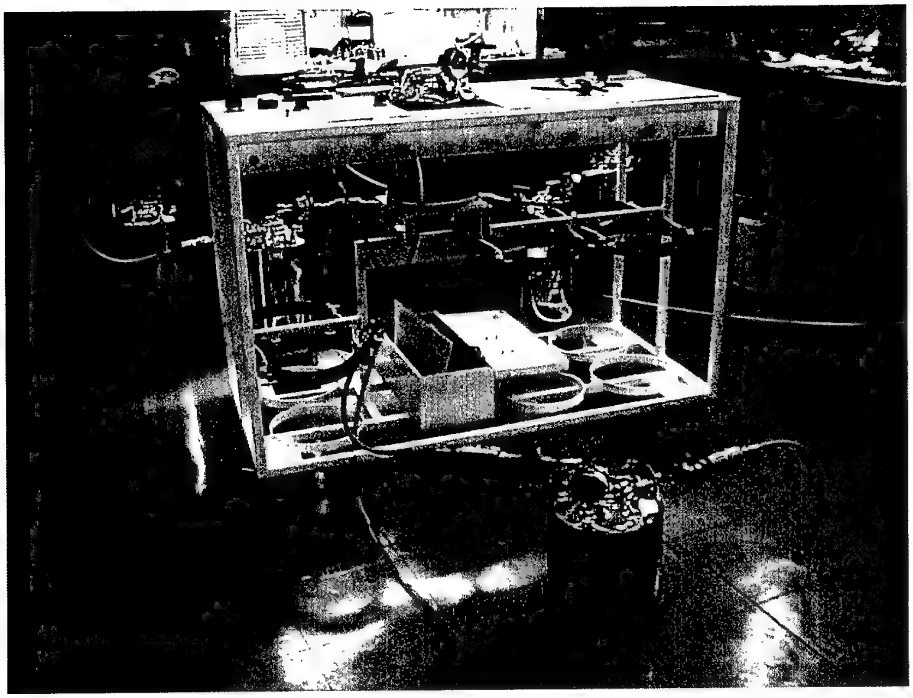

Figure 4 - Final Production Rig in DSTO Laboratory

2.2 Experimental Design

2.2.1 Test Pipe Descriptions

Due to the diverse range of aircraft and hence oxygen pipes in RAAF service, it was considered not practical to test each oxygen system pipe design. Instead, representative pipes were chosen to encompass all of the internal diameters used by the RAAF in their oxygen systems and to include all of the common materials used in oxygen systems. Test pipes were obtained from a range of sources and included both aircraft and oxygen workshop oxygen system pipes.

Table 1 - Pipe Descriptions

OD (inch)	ID (mm)	Pipe Description	Materials	Connections	No. of pipes joined	Total pipe length (metres)	Internal surface area (sqft)
1/2	10.3	Oxy workshop	Stainless steel	Swagelok	1	2.22	0.77
3/8	7.24	Oxy workshop	Copper	Swagelok	1	4.0	0.98
5/16	6.9	P3 aircraft	Stainless steel	Sierracin-harrison	3	3.72	0.87
5/16	6.17	FA-18	Aluminium	AN	10	3.27	0.68
1/4	3.9	Initial trial pipes	Stainless steel	Swagelok	3	4.0	0.56
1/8	3.0	HS748 aircraft	Copper	Brass BSPP	4	7.3	0.78

The rationale for this pipe cleaning equipment and procedures is the need for turbulence to suspend adhered particulate and dissolve NVR from the internal surface of pipes. To achieve this, and limit particulate resettling, turbulent flow is required throughout the pipe. Turbulent flow is generally considered to be initiated at around a Reynolds number of 4000 and is fully established at a Reynolds number of 5000 [7]. Table 2 list the calculated flowrate for the onset of turbulent flow using the Reynolds equation.

$$(1) \qquad N_{\mathrm{Re}} = \frac{\rho V D}{\mu}$$

Where: N_{Re} is the Reynolds Number
ρ is the density of the solvent
V is the velocity of the solvent
D is pipe internal diameter
μ is the viscosity of the solvent

Table 2 – Turbulent Flowrates for HFE-71DE and HFE-7100

Pipe description	ID (mm)	Minimum turbulent flowrate HFE-7100 (ml/min)	Minimum turbulent flowrate HFE-71DE (ml/min)
1/2″ SS	10.3	750	612
3/8″ Copper	7.24	532	435
5/16″ P3	6.9	516	423
5/16″ FA-18	6.17	468	385
1/4″ SS	3.9	296	243
1/8″ HS-748	3.0	225	183

2.2.2 Cleanliness Assessment Procedures

To assess the cleaning efficiency of the various cleaning rigs and procedures the test pipes were first dirtied using a prepared contaminant. The contaminants used are shown in Table 3. The greases were suspended in solvents. Both "Aeroshell" grease and "Krytox" have solid builders that could not be dissolved. In these instances a suspension was used.

Aluminium swarf was prepared by filing an aluminium block with a fine metal file and sieving the generated swarf. Two sieved fractions were then collected (<53 microns and 53-103 microns) and suspended in either CFC-113 or HFE-71DE. Aluminium was preferred due to its lighter weight that enabled a temporary suspension to be achieved. Heavier metals were unable to be suspended in solvents.

Table 3 - Contaminant Preparation

Contaminat	Supplier	Delivery solvent	Amount added
"Krytox AB"	Dupont	CFC-113	10%w/v
"Aeroshell Grease 6"	Shell	CFC-113 or HFE-71DE	5% w/v
OM-15 hydraulic fluid	Esso DSD-9650-66-038-5321	Pet. spirit 60-80 °C	5%w/v
Aluminium Swarf		CFC-113 or HFE-71DE	1-2%w/v

Once a suspension was prepared, an amount that would provide approximately 33 mg/sqft was delivered into the test pipes. For instances where more than one pipe was used, the contaminant was delivered in smaller amounts at each pipe connection. The suspension was allowed to flow down the pipes using gravity and the pipe was rotated to assist the coating of all of the internal surfaces. Care was taken to ensure that excess contaminant did not flow out of the pipes. The set of test pipes were then joined ready for the cleaning test and the ganged pipes were purged with a gentle stream of high purity nitrogen to dry off any excess solvent.

2.3 Analytical Methods

To analyse the pipes for residual NVR and particulate contamination following cleaning, a non-direct analysis method must be employed because direct inspection of the internal pipe surfaces is not possible. The need for a non-direct analysis method results in a two step process. In the first step, the internal pipe surface is indirectly sampled by extracting the contaminants from the surface with a test solvent, these are known as the verification extraction procedures and are discussed in Section 2.3.1. In the second step, the extracted test solvent is analysed for residual extracted NVR or particulate, these are discussed in Sections 2.3.2 and 2.3.3, respectively.

2.3.1 Verification Extraction Procedures.

There are a number of standard methods that describe how to extract contaminants from component and pipe surfaces. During the course of the pipe trials two of these methods were used. In addition, two methods to deliver the solvent to the test pipes were used. The methods for delivering the extraction fluids and verification procedures are described below.

2.3.1.1 Original Extraction Method of Delivery

The original method involved placing a measured amount of CFC-113 in a cleaned pressure vessel and connecting the pipes directly to the outlet via an in-line 2 micron filter. The CFC-113 was flushed through at the appropriate flowrate by varying the nitrogen pressure to the pressure vessel. The CFC-113 was then collected at the pipe outlet and analysed for particle or NVR.

2.3.1.2 Modified Extraction Method of Delivery

A modified method was used in later trials to avoid the need to reconnect the test pipes to an additional pressure vessel. In the modifed extraction method a measured amount of CFC-113 was placed in the final flush pressure vessel and this vessel was used to deliver the extraction fluid. The final flush pressure vessel was thoroughly cleaned and dried every time solvents were changed using clean low lint cloths.

2.3.1.3 ASTM F303 Verification Method

Two methods for the verification were employed. The first was based on ASTM method F303 practice B "Standard Practice for Sampling Aerospace Fluids from Components"[8]. This practice requires flushing with at least 10 times the internal volume of pipes with solvent at a flow rate of greater than 500 ml/min, while continually vibrating the pipes to encourage maximum suspension of particulates. 600 ml of Freon was found to be sufficient to achieve the 10 times internal volume for most of our pipes tested. The vibration was provided by hand shaking the pipes during extraction.

2.3.1.4 ASTM G93 Verification Method

The second method was based on ASTM Method G93 "Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment used in Oxygen-Enriched Environments"[2] which outlines a method for extracting surface particles. This requires pouring or flushing 100 ml of solvent over test components of at least 1 sqft surface area. This was difficult with our pipes because we did not have 1 sqft available in any single pipe. Flushing is the only viable option to wet the internal surfaces of the

test pipes. This standard gives very little guidance on flow rates, which will have a large effect of the efficiency of which particulates are dislodged from the surfaces.

In general G93 is a less demanding extraction method, but it is more directly related to the particulate standard adopted by the RAAF. In later tests, both extraction methods were combined by doing one initial flush with 100 ml of Freon without adding additional vibration to the pipe at a flow rate greater than 500 ml/min, and then flushing another 500 ml of Freon through at the same flow rate while shaking the test pipe or pipes. The initial 100 ml sample when counted was used to give the result for the G93 test and the two results were added together to give the result based of ASTM F303 Practice B.

2.3.2 Non-Volatile Residue

The extract was analysed for non-volatile residue by evaporating the bulk of the solvent down using a rotary evaporator, drying the remainder completely in an oven, and weighing the residue according to ASTM Method F331-00 "Standard Method of Solvent Extract from Aerospace Components (Using Rotary Flash Evaporator)" [9].

2.3.3 Particulates

For particulate analysis the extract from the pipes were sized and counted using ASTM Method F312 "Standard Methods for Microscopal Sizing and Counting Particles from Aerospace Fluids on Membrane Filters."[10] In addition, a blank was obtained and subtracted from the results to compensate for extraneous environmental particulate contamination and particle load from the filter holder and connections etc.

During testing, particles were counted for size ranges 25-50 micron, 50-100 micron, 100-175 micron and greater than 175 micron. This covers the RAAF particle specification, but also allows some assessment of the smaller particles in the less than 50 micron ranges.

3. Results

The results outlined below were performed using the different rigs as outlined in Section 2.1 as the newer designs became available for testing. The results for the pipes tested will be presented separately.

3.1 1/8" Copper HS748 Pipes

The 1/8" copper pipes used on the HS748 aircraft are the smallest oxygen pipes in use by the RAAF. The pipes have a brass nipple which is silver soldered to the pipe and are connected using brass BSPP connections. Figure 5 illustrates the pipe end and fittings.

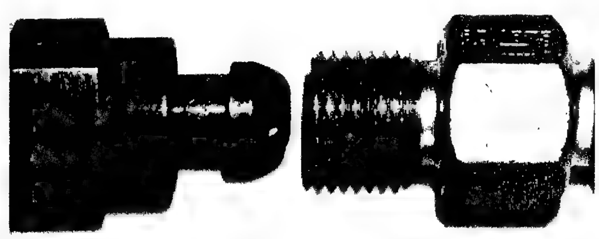

Figure 5 – HS748 pipe fittings and union.

The 1/8" copper HS748 pipes were the first aircraft pipes tested and were cleaned using the pre-production rig (Section 2.1.2). These pipes were also used for the main procedure development and hence much more testing was conducted using these pipes than later pipe trials. They were chosen for initial testing because the HS748 aircraft were undergoing a major refit of new oxygen system pipes and the cleaning of these new pipes was a priority for the RAAF.

It was fortuitous that these pipes were chosen for initial testing as they proved to be the most demanding due to the small inside diameter and the unusual pipe connections. The small diameter meant that a high backpressure was present in the pipes and the highest nitrogen pressure to the delivery vessels was required to push the HFE solvents through at turbulent flowrates. Also, the soldered brass connection can often result in a void at the join that could trap particles.

During the testing of these pipes it was found that the need to reconnect pipes onto the verification vessels was adversely affecting the results. Consequently the results for this trial are divided into two sections, the first section using the original verification extraction method (Section 2.3.1.1) and the second section using the modified extraction method (section 2.3.1.2).

3.1.1 HS748 Pipes using Original Verification Method

The results for the first series of experiments on particulate removal are shown in Table 4. A more detailed table of the conditions of each of the trials can be found in Appendix A.

Table 4 - Results for flushing rig using HS 748

Trial Number	Pipe Description	Pipe Length (metres)	Internal Surface Area (sqft)	Internal Volume (ml)	Test Description	25-50 (micron)	50-100 (micron)	100-175 (micron)	>175 (micron)
					Target	Unlimited	5	1	0
1	5 old HS748 Cu pipes with ISO connectors and BSPP unions	9.08	0.92	64	F303	146	67	35	8
					Blank	28	6	0	0
					F303-Blank	118	61	35	8
After trial prefilter was found to be blocked and was replaced									
2	5 old HS748 Cu pipes with ISO connectors and BSPP unions	9.12	0.95	66	F303	109	58	5	1
					Blank	28	6	0	0
					F303-Blank	81	52	5	1
3	5 old HS748 Cu pipes with ISO connectors and BSPP unions	9.12	0.95	66	F303	205	72	26	12
Trial 3 – pipes were shaken during the recycle stages									
4	5 old HS748 Cu pipes with ISO connectors and BSPP unions	9.12	0.95	66	F303	45	11	4	3
					Blank	20	2	0	0
					F303-Blank	25	9	4	3
Trial 4 onwards – the ISO Fittings were replaced with BSPP.									
5	5 old HS748 Cu pipes with ISO connectors and BSPP unions	9.12	0.95	66	F303	818	476	3	3
Trial 5 – Braided hose connection was cleaned by submersion in HFE-7100. Braid was also rinsed. Braided hose contains many particles that probably contaminated the result.									
6	5 old HS748 Cu pipes with ISO connectors and BSPP unions	9.12	0.95	66	F303	84	26	11	2
					Blank	19	1	0	0
					F303-Blank	65	25	11	2
					F303 repeat P1	45	10	1	0
					F303 repeat P1	33	2	1	0
					F303 repeat P2	57	10	2	1
The F303 extraction was done three times in the P1 direction, the direction was reversed and another F303 extraction performed. This was done to test whether particles are being trapped in voids.									
7	5 old HS748 Cu pipes with ISO connectors and BSPP unions	9.12	0.95	66	F303	34	4	3	2
					Blank	14	3	0	0
					F303-Blank	20	1	3	1
Trial 7 - Flow direction was frequently switched from the P1and P2 directions during recycle stages, with tapping of connections.									

Table 4 continued - Results for flushing rig using HS 748

Trial Number	Pipe Description	Pipe Length (metres)	Internal Surface Area (sqft)	Internal Volume (ml)	Test Description	25-50 (micron)	50-100 (micron)	100-175 (micron)	>175 (micron)
					Target	Unlimited	5	1	0
8	2 old HS748 Cu pipes with ISO connectors	5.77	0.58	41	F303	78	11	1	1
					Blank	23	2	0	0
					F303-Blank	55	9	1	1
11	2 old HS748 Cu pipes with ISO connectors	4.49	0.46	32	G93	5	0	1	0
					F303	39	8	4	1
					Blank	15	2	0	0
					G93-Blank	0	0	1	0
					F303-Blank	24	6	4	1
Trial 11 – 8 micron membrane in line filter placed between pipes.									
14	5 old HS748 Cu pipes with BSPP connectors and HS 748 unions	9.12	0.95	66	G93	139	17	1	0
					F303	160	19	1	1
					Blank	7	0	0	0
					G93-Blank	132	17	1	0
					F303-Blank	153	19	1	1
15	5 old HS748 Cu pipes with Manufactured connection And HS748 unions	9.12	0.96	67	G93	111	13	1	1
					F303	144	14	2	1
					Blank	11	2	0	0
					G93-Blank	100	11	1	1
					F303-Blank	133	12	2	1
Trial 15 - 5 minute recycle only.									

As can be seen from the results, no trials met the RAAF specification for particulate removal. During the trials a number of improvements were also made to the rig set-up and operation.

Trials one to three used the ISO conversion fittings supplied by Rosebank Engineering. These have a flat mating surface that was observed to dig into the dome brass end fittings on the HS 748 pipes. From Trial 4 onwards BSPP conversion fittings were used instead, which have an inverted cone shape. These fittings closely match the supplied connectors used for the HS 748 pipe system. The results using the ASTM F303 extraction method are shown in Figure 6. An improvement in particulate removal was immediately noticeable, although the improvement was not great enough to meet the G93 175 specification.

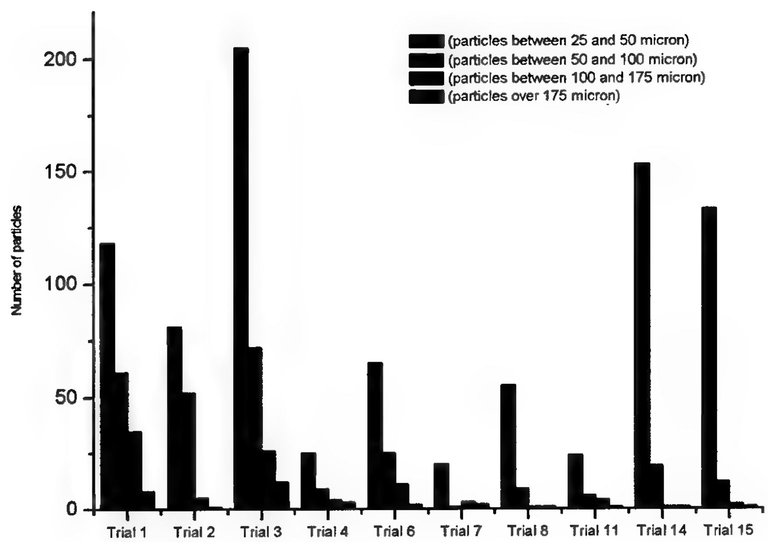

Figure 6 - Results HS 748 pipe cleaning for Aluminium particulate removal using the PPRig.

Trial 5 was discounted due to extraneous contamination that occurred when washing the end connectors on the flexible SS braided hose on the final flush rig. A separate flush of the braided hose showed that the braid traps a substantial amount of metallic particulate. We suspect that when we flushed the end fittings, some of the solvent would have also flushed the braiding causing the movement of particulates on to the end fitting on the final flush rig and contaminated Trial 5. Stainless steel braided hose was not used on the final flushing rig to avoid this in future.

Trial 6 was a repeat of Trial 4, but conducted at slightly higher flow rates, due to replacement of a partially blocked 2-micron filter element. The results of Trial 6 were not as good as the results from Trial 4. It is not clear with the limited data available whether this is associated with the flow rate change, or just an indication of level of normal variation in the results. To check whether the fittings are accumulating particles in the void in the connectors, a Freon extraction was done three times in the same direction, the direction reversed and another extraction performed. The results are shown in Figure 7 and show a significant increase occurring when the flow direction was reversed. This is consistent with trapped particles being released from voids or additional particles being produced during reconnection to the Freon extraction vessel.

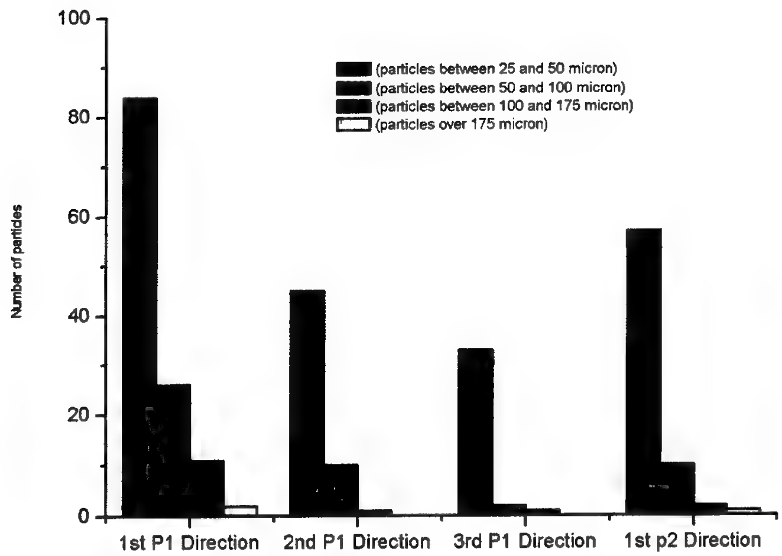

Figure 7- Consecutive Freon F303 Extractions Following Trial 6 (results not corrected for background blank).

If voids were present in the end fittings and trapping particulates, reversing the flow direction more frequently and resuspending the trapped particles more often would increase the possibility of successful elimination from the pipes. During Trial 7, the flow direction was changed approximately every 5 minutes, 12 times overall. The results in Figure 6 show an improvement in particle removal.

Trial 8 was conducted using only 2 pipes in order to reduce the number of connections. The results for this are not particularly good, since more particles were present than in the previous Trial 7 which had a larger surface area. However, when the brass dome end fittings were wiped with a clean lint free cloth, visible dirt was observed. This could indicate that particles were being trapped and were accumulating in the end fittings.

Trial 11 was conducted with the same two pipes but with a membrane filter unit placed between these pipes. In this way, particles removed from one pipe will not have to travel through another pipe before eventually being removed. The results show a significant improvement over Trial 8 when no filter was used.

Trial 14 was done with the same set-up as Trial 4, but using the Brass unions obtained from RAAF East Sale for the HS 748 pipes.

Trial 15 is a repeat of previous trials but used only a five-minute recycle time for HFE-71DE and HFE-7100. This trial also used the newly manufactured brass connection to join the HS 748 pipes to the pre-production rig. Comparing this result from previous results, it is unclear whether 5 minutes is an acceptable time, as the results are inconclusive (Figure 6).

The best results were obtained in Trials 7 and 11 where the flow direction was changed frequently or when a filter was placed in between pipes. Trial 4 also had a reasonable result. The best results obtained do not meet the G93 175 standard. However, these results are based on the F303 verification method and not the applicable G93 verification method.

When the less rigorous G93 extraction method was used for Trial 11, the result met the standard (Table 4), although only 0.46 sqft was used, not 1 sqft. If the result is multiplied by 2.17, to correct for the lower surface area, then this trial would fail in the 100 to 175 micron size range. However, with such small numbers of particles being extracted, a normal distribution of particles should not be assumed which makes simple extrapolation of results difficult.

3.1.2 HS748 Pipes using the Modified HS748 Extraction Method.

Following the higher than expected particle results listed in the previous section the extent of particle generation during the reconnection of pipes was investigated. A preliminary study of particle generation in pipe connections was performed. The results for this have been reported elsewhere [11].

The preliminary tests showed that particle generation during each disconnection and reconnection of HS748 pipes can be significant. Consequently, the modified verification extraction procedure was developed and the trials with the HS748 pipes repeated. The results for this testing are shown in Table 5 and Figure 8

This next series of tests used the pre-production rig and the same draft cleaning instructions used in the previous Trials 1- 15, but with a couple of modifications.

Four newly manufactured and specialist cleaned HS 748 high-pressure copper pipes (2 x No. 99 and 2 x No. 100 pipes) were used with one flexible hose only on the Recycle rig. The pipes were dirtied as normal, but before connecting to the Recycle rig nitrogen gas blowdown was used to purge each pipe for 2 minutes.

For Trials 16 through 18 the pipes were connected and subjected to a 15-minute HFE-71DE and HFE-7100 rinse in each direction, as per draft instruction 2 [3]. For Trial 19, the time for the HFE-71DE and HFE-7100 recycle flushes was shortened to 5 minutes in each direction. For Trial 20, the recycle flush time was 5 minutes, but no initial nitrogen gas blowdown was performed.

The Final Rinse rig was then readied for the final rinse and Freon extraction, because this rig was also going to be used for the final Freon verification, care was taken to ensure that it was thoroughly cleaned and free from contamination. To achieve this, Freon was added to the final rinse solvent reservoir and a filter unit added directly on to the rig without any pipes connected and cleaned until no further improvement in particle counts were obtained with subsequent Freon flushes. At this point, the blank was obtained. The Freon was then removed from the reservoir and HFE-7100 added.

The four pipes, while still connected were then attached to the Final Rinse rig and subjected to the same final rinse. The pipes were kept connected to reduce the number of connections and ensure that no connection was needed between the final rinse and the Freon extraction.

The HFE-7100 was removed and Freon added to the solvent reservoir and the normal G93 and F303 extraction methods were performed. The results are shown in Table 5, with the G93 and F303 results shown graphically in Figures 8 and 9, respectively.

Table 5 - Results for modified extraction method.

Trial Number	Pipe Description	Internal Surface Area (sqft)	Test Description	25-50 (micron)	50-100 (micron)	100-175 (micron)	>175 (micron)
			Target	Unlimited	5	1	0
16	4x HS747 high pressure copper pipes.	0.78	G93	14	2	1	0
			F303	55	13	2	1
			Blank	9	3	0	0
			G93-Blank	5	0	1	0
			F303-Blank	46	10	2	1
17	4xHS748 high pressure copper pipes	0.78	G93	31	12	1	0
			F303	50	16	1	0
			Blank	15	10	0	0
			G93-Blank	16	2	1	0
			F303-Blank	35	6	1	0
18	4 x HS748 high pressure copper pipe	0.78	G93	5	0	0	0
			F303	35	2	1	0
			Blank	10	2	0	0
			G93-Blank	0	0	0	0
			F303-Blank	25	0	1	0
19	4 x HS748 high pressure copper pipe	0.78	G93	2	0	1	0
			F303	10	3	4	0
			Blank	6	0	0	0
			G93-Blank	0	0	1	0
			F303-Blank	4	3	4	0
20	4 x HS748 high pressure copper pipe	0.78	G93	4	3	0	0
			F303	11	9	3	0
			Blank	3	0	0	0
			G93-Blank	1	3	0	0
			F303-Blank	8	9	3	0
21	4 x HS748 high pressure copper pipe	0.78	G93	5	0	0	0
			F303	10	6	4	0
			Blank	8	0	0	0
			G93-Blank	0	0	0	0
			F303-Blank	2	6	4	0
22	4 x HS748 high pressure copper pipe	0.78	G93	6	0	0	0
			F303	17	2	2	0
			Blank	3	1	0	0
			G93-Blank	3	0	0	0
			F303-Blank	14	2	2	0
23	4 x HS748 high pressure copper pipe	0.78	G93	1	0	1	0
			F303	10	8	3	0
			Blank	3	0	0	0
			G93-Blank	0	0	1	0
			F303-Blank	7	8	3	0
24	4 x HS748 high pressure copper pipe	0.78	G93	0	0	0	0
			F303	8	18	4	0
			Blank	3	0	0	0
			G93-Blank	0	0	0	0
			F303-Blank	5	18	4	0

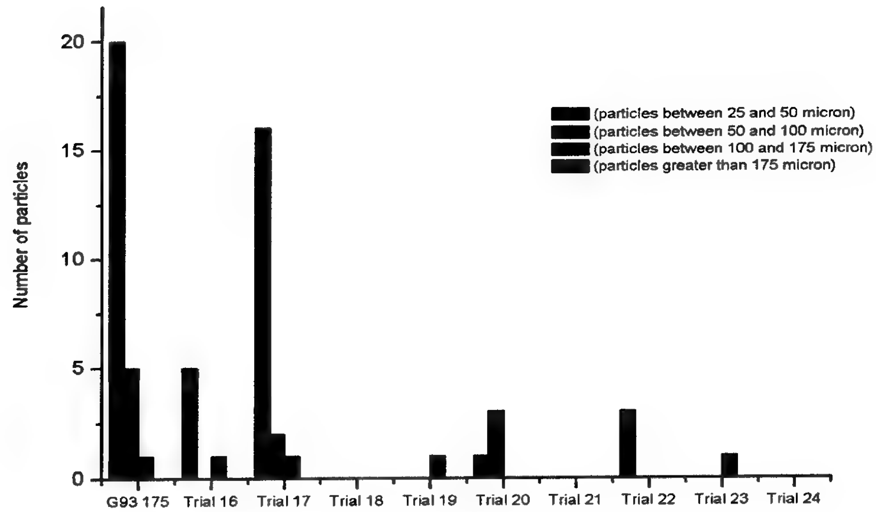

Figure 8 - Results for the G93 tests using four HS748 copper pipes permanently ganged and the modified Freon extraction method.

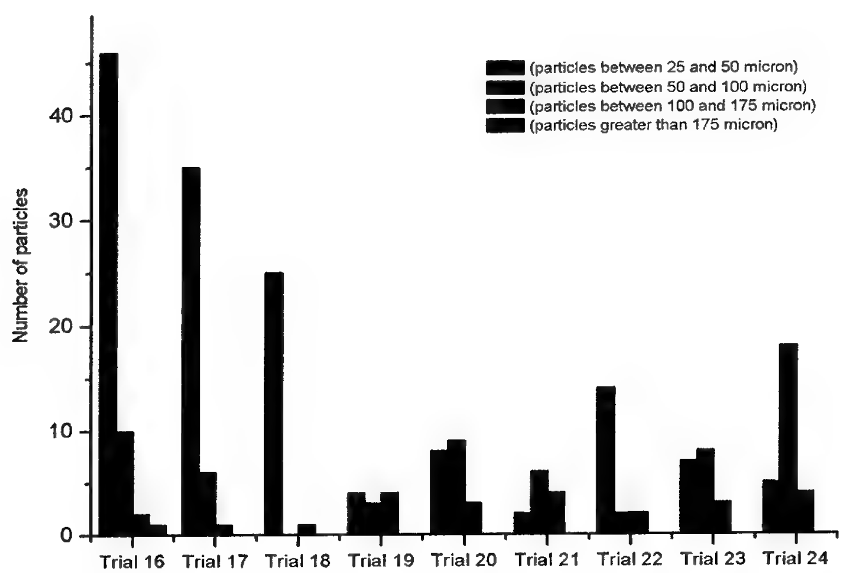

Figure 9 – Results for the F303 tests using four HS748 copper pipes ganged and the modified extraction method.

From Figure 8 all of the trials performed using the permanently ganged new HS 748 pipes and the modified extraction method met the G93 175 particle specification when tested using the G93 method. Trial 18 also met the specification when the more demanding F303 test was used (Figure 9). In all cases, we are subtracting a blank because the testing is not being performed in a proper Class 100 clean room and some environmental load can be expected to interfere with the results (which is an option in ASTM method F312).

The results of Trials 16-18 demonstrate that the pre-production rig can meet the G93 175 particle specification using draft instruction 2, with an initial nitrogen gas blowdown.

Further trials were performed to determine if the process could be speeded up without compromising cleanliness. Trials 19 and 20 were conducted using a 5 minute recycle in each direction and the results for the G93 test also meet the particle specification. Trial 19 used the initial Nitrogen purge and Trial 20 had no nitrogen purge. It was noted that in the entire F303 tests of Trials 16-24, some aluminium swarf particles were evident in the 50-175 micron size ranges. Figure 10 is a photomicrograph of the swarf particles observed in the F303 test of Trial 24.

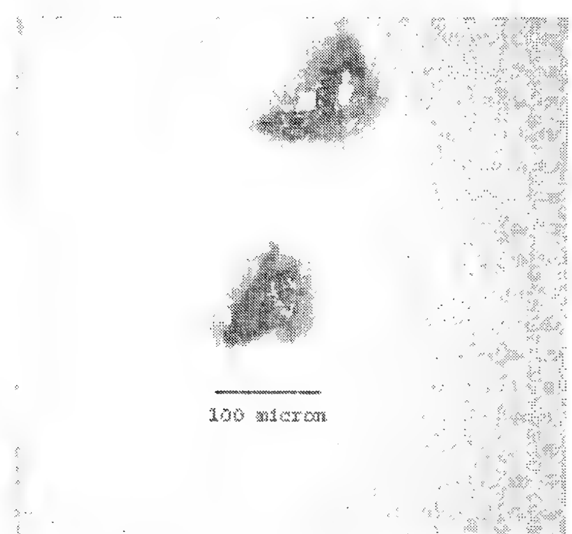

Figure 10 - Observed swarf particles in Trial 24 using F303 Freon extraction.

The swarf particles pictured in Figure 10, are grey metal particles, which are not copper or brass, and are therefore, not caused by particle generations from the copper or brass materials present in the HS748 pipes. The particles shown are consistent with the aluminium swarf particles introduced into the pipes as particle contamination prior to cleaning. Therefore, the presence of these particles is indicative of some of the original contamination not being fully removed. It is also worth noting that these particles do

not show up in the G93 extraction. It appears these particles must be trapped somewhere and are only resuspended on shaking. The HS748 fittings and unions provide one source where voids are present and particles may be lodged.

To test this observation Trials 22 and 23 were the same as Trials 19 and 20 but the test pipes in Trials 22 and 23 were shaken for the last 30 seconds for each recycle flush using HFE-71DE and HFE-7100 in each direction, with no initial nitrogen purge. This resulted in two minutes of shaking overall. No difference was observed between the 5-minute runs with shaking and the 5-minute runs without shaking. Therefore, some shaking did not remove trapped particles in the ganged pipes.

Trials 21 and 24 were a repeat of the 15 minute solvent recycle process, but without the initial nitrogen flush. Again no major differences were observed over the scatter of the data obtained.

Comparing all of the results shows that there is a general improvement in the particle count in the 25-50 micron size range after the initial Trials 16-18. This is probably caused by the stronger Freon solvent gradually cleaning up the HFE-7100 final rinse rig. However, this only appears to be relevant at the smallest particle size range. In Figure 9, for the F303 validation method, no trend is noticeable for the larger particles.

In addition, there appears to be little observable difference between the slight changes to the cleaning methods used. The trials with the initial nitrogen purge (Trials 16-19) show no noticeable improvements over trials 20-24 where no nitrogen purge were performed. Also, trials that used only the 5 minute recirculation times (Trial 19 and 20) showed no effect of a shortened recirculation time.

During this and subsequent trials we have had to take care of the filter unit used as a visual inspection of the final rinse effluent as this can also be subjected to interference from the particle generation already discussed. In addition the stainless steel screw used to assemble the stainless steel filter holder can also be a source of particle contamination.

We have found that the first white membrane used for the first final rinse always has visible particles and sometimes the second rinse membrane also has visible particles. This is not surprising as the filter has to be added before the final rinse and the pipes have to be connected to the Final Rinse rig. This is therefore, not testing only the pipe cleanliness, but also particle generation.

3.2 1/4" Stainless Steel Pipes

The 1/4" stainless steel pipes were the first pipes tested using the proof of concept rig as outlined in Section 2.1.1. These test pipes and the rig was used to determine the efficiency of the equipment and procedures to achieve the non-volatile residue specifications.

3.2.1 Non-volatile residue Cleaning Performance

Initial testing was performed using HFE-7100 only in the two stage process. These results were obtained by flushing the contaminated pipes with 10-15 litres of recycled HFE-7100 at flowrates between 2 and 3 l/min in one direction, followed by a 600 ml final flush with unused HFE-7100 at 0.5 to 1.0 l/min. The verification method used was the more thorough F303 method outlined in Section 2.3.1.3. The results are shown in Table 6.

Table 6 - Results for NVR Removal using HFE-7100 only.

Contaminant	Average Final Surface NVR (mg/sqft)
"Aeroshell" Grease	0.5±0.4
OM-15 Hydraulic fluid	6±4
"Krytox" Grease	1.3±0.4

HFE-7100 was found to be sufficient to remove "Krytox" and "Aeroshell" grease, the results for OM-15 were more varied and the testing was repeated using an initial 600 ml flush with HFE-71DE, a much stronger degreaser. The HFE-71DE was flushed through at a flowrate of approximately 1.0 litres/min. The results are shown in Table 7.

Table 7 - NVR Removal using 71DE and HFE-7100.

Contaminant	Average Final Surface NVR (mg/sqft)
"Aeroshell" Grease	0.6±0.6
OM-15 hydraulic fluid	1±1
"Krytox" grease	1.0±0.4

From Tables 6 and 7 it is observed that the flushing method using HFE solvents can readily achieve the RAAF's non-volatile residue specification. For later rigs and procedures that flush much greater volumes of solvents through the pipes, there a high degree of confidence that the equipment and solvents will achieve the NVR specification. Especially, where it is shown that "Krytox", the most likely contaminant to be encountered in the internals of aircraft oxygen system pipes, was readily removed with only small amounts of HFE-7100.

3.2.2 Particulate Assessment

The initial particle testing performed on the proof of concept rig was not successful. The testing with the 1/4″ pipes was done prior to the HS748 testing and used the original extraction method. The failure to achieve the particle cleanliness specification was also probably caused by particle generation during the reconnection of pipes to the extraction vessel.

3.2.3 Assessment of contaminant recovery using the original extraction method

To ensure that the results obtained in the above analysis were reliable, a recovery analysis was performed on the dirtied pipes. The pipes were contaminated using the method outlined in Section 2.2.2, and extracted using the original extraction method outlined in Section 2.3.1.1 without any cleaning in between. The weight recovered was then divided by the amount of contaminant that was nominally added to the pipe. This nominal amount was found by adding the contaminant to a pre-weighed beaker instead of the pipe and measuring the final weight after the carrier solvent has totally evaporated away. Table 8 lists the calculated recoveries obtained for the various greases

Table 8 - Recovery of Contaminant using the F303 Method.

Contaminant	Amount recovered (mg)	Amount nominally added (mg)	% Recovery
"Krytox"	6.8	8.2	83%
"Aeroshell" Grease	12.2	16.6	73%
OM-15	10.9	12.9	84%
Particulates	10	16	62%

Based on this table we can see that the reliability of the method for greases is very good but the removal of particulates was less reliable.

3.3 5/16″ Aluminium FA18 Pipes

The FA18 aluminium oxygen system pipes were tested for particulates on the Production rig (Section 2.1.3). The extraction method was the modified verification method (Section 2.3.1).

The conditions of the tests are outlined in detail in Appendix A. In summary, HFE-71DE was flushed through for 5 minutes in both directions at 1 l/min. HFE-7100 was then flushed through for 5 minutes at 1.0 l/min in both directions, the recirculating flushes were followed by a final rinse with clean HFE-7100 at 0.6 l/min.

Table 9 lists the results for duplicate tests with the FA18 pipes.

Table 9 - Results for FA-18 Aluminium 5/16" pipes

Trial No.	Pipe Description	Internal Surface Area	Test Description	No. of particles 25-50 micron	50-100 micron	100 -175 micron	>175 micron
			Target	unlimited	5	1	0
6	5/16″ Aluminium 11 pipes joined	0.68	100 ml G93	7	0	0	0
			F303	26	0	1	0
			Blank	1	1	0	0
7	5/16″ Aluminium 11 pipes joined	0.68	100 ml G93	0	0	0	0
			F303	8	0	0	0
			Blank	4	0	1	0

From the results in table 9 it is evident that the method is efficiently removing particles from the FA18 pipes. This is particularly challenging considering the test consisted of 11 pipes ganged together. Even after the reduced internal surface area is considered, the RAAF particle specification is being met under these test conditions.

3.4 5/16″ Stainless Steel P3 Pipes

The Orion P3 stainless steel pipes with Sierracin-Harrison™ ferrule fittings and connections were tested on the pre-production rig as described in Section 2.1.2. The pipes were sourced from RAAF Base Edinburgh. The pipes were contaminated and tested for both NVR and particulate removal.

To test whether the final flush is required to achieve the NVR specifications of 3 mg/sqft, the NVR tests were performed without a final flush. That is the pipes were only subjected to recirculating HFE-71DE and HFE-7100. The contamination levels in the recirculating fluids will have a potential impact on the NVR results, as no final flush was performed. The NVR in the recirculating solvents were assessed before and after the NVR trial and are shown in Table 10.

Table 10 - NVR concentration in the recirculating solvents before and after NVR tests.

	HFE-71DE recirculating solvent (mg/l)	HFE-7100 recirculating solvent (mg/l)
Before	124.2	9.2
After	132.6	14.0

As can be seen in Table 10 the following NVR trials were performed using previously used solvents that already had some elevated NVR. Also observable is the increase in NVR. This increase confirms the that the solvents, particularly HFE-71DE, are dissolving and holding the grease contaminants.

The NVR results obtained for the pipes tested for the grease contaminants are shown in Table 11.

Table 11 - NVR for P3 5/16" Stainless Steel Pipes.

Trial Number	Contaminants	Pipe Description	Internal Surface Area sqft)	NVR (mg/sqft)
27	OM15	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	1.3
28	OM15	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	0.6
29	"Aeroshell" Grease	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	0.2

As shown by the results in Table 11, the pipe cleaning equipment and HFE solvents are capable of removing oil and greases and achieving the RAAF NVR specification of 3 mg/sqft without a final rinse. It also demonstrates that the HFE solvents can hold a reasonable level of dissolved NVR before compromising soil removal capacity

significantly. However, the NVR in the recirculating vessels will continue to accumulate and if left to accumulate indefinitely will reach a concentration that will affect the cleaning performance of the system. A solvent monitoring program at RAAF bases, to monitor NVR accumulation rates, would assist in the determining of the serviceable life of the solvents. Additional laboratory testing is recommended to determine when accumulated NVR in the HFE solvents starts to cause the 3 mg/sqft NVR surface specification to be exceeded.

Without knowing exactly how much NVR is in the recirculating solvents in the field, and the point at which NVR accumulation affects cleaning performance as measured by the surface NVR analysis, the final rinse with un-used HFE-7100 of known purity is considered necessary.

The results for the particulate testing using both the G93 and F303 extraction methods are shown in Table 12.

Table 12 - Particulate Removal from P3 Pipes

Trial Number	Pipe Description	Internal Surface Area (sqft)	Test Description	25-50 (micron)	50-100 (micron)	100-175 (micron)	175 (micron)
			Target	unlimited	5	1	0
26	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	G93	11	0	1	
			F303	186	4	1	
			Blank	20	0	0	
			G93-Blank	0	0	1	
			F303-Blank	166	4	1	
30	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	G93	6	0	0	0
			F303	27	10	9	0
			Blank				
			G93-Blank				
			F303-Blank				
31	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	G93	4	2	0	0
			F303	8	11	2	0
			Blank				
			G93-Blank				
			F303-Blank				
32	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	G93	3	8	4	2
			F303	16	8	5	2
			Blank				
			G93-Blank				
			F303-Blank				
33	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	G93	3	0	1	0
			F303	14	8	2	0
			Blank				
			G93-Blank				
			F303-Blank				
34	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	G93	33	10	10	1
			F303	50	27	22	2
			Blank				
			G93-Blank				
			F303-Blank				
35	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	G93	6	1	1	0
			F303	24	5	1	0
			Blank				
			G93-Blank				
			F303-Blank				
36	3 x P3 pipes I.D. 6.9mm plus unions and conversion fittings	0.87	G93	5	6	3	0
			F303	13	8	6	0
			Blank				
			G93-Blank				
			F303-Blank				

During these trials a number of parameters were changed. The full conditions for each trial are presented in Appendix A.

Trial number 26 consisted of cleaning 3 pipes as received from the squadron. No additional contamination was added. The pipes were cleaned for the standard 5 minutes in each direction.

Trial number 30 was a repeat of Trial 26, but the pipes were artificially contaminated with Aluminium swarf as outlined in Section 2.4.2.

Trial number 31 was a repeat of trial number 30, but the pipes were cleaned for 15 minutes in each direction instead of the previous 5 minutes.

Trial number 32 was a repeat of trial number 30, but the pressure in the vessel was increased to 300 KPa. The flow duration was again 5 minutes in each direction.

Trial number 33 was a repeat of trial number 30, but the pressure was again increased to 500 KPa. Consequently, Trials 30, 32 and 33 are the same except the resultant flowrate is increased through the pipes (Appendix A).

The results of the above trials are shown in Figure 11.

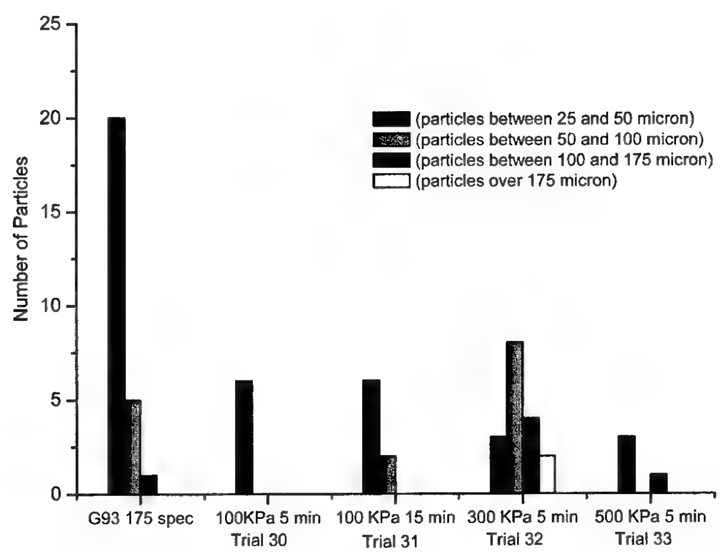

Figure 11 – G93 results for P3 pipes for a variety of different conditions.

From the data displayed in Figure 11 it is observed that the only time the G93 specification was not achieved was with the 300 KPa trial. Why this should be higher than either the 100 KPa or the 500 KPa experiment is unknown. However, it does demonstrate that there appears to be no advantage in increasing the pressure in the delivery vessel, and thereby increasing the solvent flow rates through the pipes beyond a flowrate sufficient to achieve full turbulent flow.

Also increasing the solvent flow duration has no noticeable affect on the cleaning performance with particulate removal, beyond the initial 5 minute in each direction.

Trials 34 to 36 involved newly manufactured pipes that had been through previous specialist cleaning stages. Trial 34 had been sent for a specialist clean at RAAF Williamtown before testing. Trials 35 and 36 were not specialist cleaned, but had a HFE-7100 wetted pull through used as a precleaning step. The Liquid and Gaseous Dry Breathing Oxygen Maintenance Instructions AAP 7055.001-99 [6] describes the method for a pull-through. In summary it involves wetting a low-lint cloth with a solvent, tying this to nylon fishing line and threading this through the pipe. The solvent impregnated cloth is then forced through the pipe.

Figure 12 list the affect of the different precleaning procedures has on P3 pipes as received from the squadron. These are more relevant to the actual conditions of the pipes before undergoing precision cleaning using the pipe cleaning equipment.

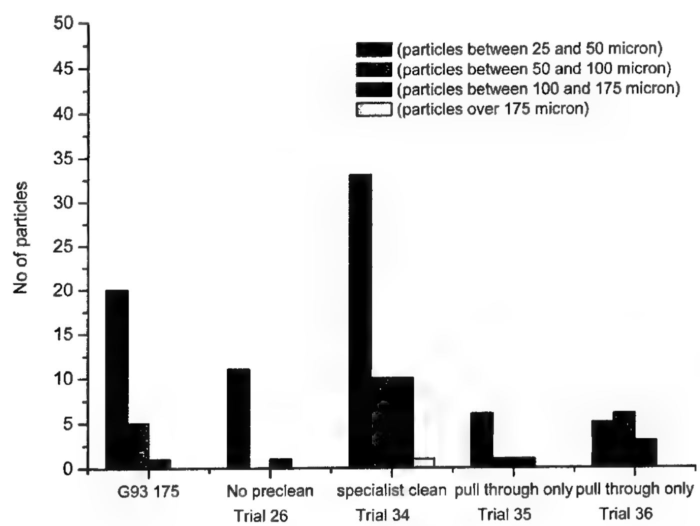

Figure 12 – Affect of different pre-treatments on results with P3 pipes.

From Figure 12, the contamination is still present after cleaning in the specialist-cleaned pipes. We have previously found, when cleaning up our cleaning rigs made from stainless steel, that stainless steel pipes after manufacture can be difficult to clean to the RAAF specifications. There are usually a lot of particles present in these pipes carrying over from the pipe manufacturing process. The use of a pull through prior to precision cleaning is therefore highly recommended with stainless steel pipes, especially newly manufactured pipes.

It is also worth noting that the G93 was not always met with the newly manufactured RAAF pipes even when a pull through is employed. This should not be a problem as

the pipe cleaning procedures call for a visible inspection of the membrane in the final flush rig, and if particulate contamination is seen, then the pipe must undergo a partial or full re-clean, as necessary.

3.5 3/8" Copper Pipes

A 3/8" copper pipe, similar to the pipes used in workshop pipe systems that must be cleaned to the same RAAF specifications, was tested. These pipes were tested for particulates on the Production rig (Section 2.1.3). The extraction method was the modified method Section 2.3.1.

The conditions of the tests are outlined in detail in Appendix A. In summary HFE-71DE was flushed through for 5 minutes in two directions at 1.0 l/min. HFE-7100 was then flushed through for 5 minutes at 0.7-0.8 l/min in both directions, followed by a final rinse with clean HFE-7100 at 0.7 l/min.

Table 13 lists the results for the 3/8" pipe.

Table 13 - 3/8" Copper Pipe

				No. of particles			
Trial No.	Pipe Description	Internal Surface Area	Test Description	25-50 micron	50-100 micron	100 -175 micron	>175 micron
			Target	unlimited	5	1	0
1	3/8" Copper 3 metre	0.98 sqft	100 ml G93	4	1	0	0
			F303	14	6	0	0
			Blank	1	0	0	0
2	3/8" Copper 3 metre	0.98 sqft	100 ml G93	0	0	0	0
			F303	3	2	0	0
			Blank	2	0	0	0

From the results in Table 13 it is evident that the procedure and equipment is capable of removing swarf to achieve the RAAF's particulate specification.

3.6 1/2″ Stainless Steel Pipes

A 1/2″ stainless steel pipe was also tested, since many oxygen workshops use similar pipes in their gas distribution systems that must be cleaned to the same RAAF specifications. These pipes were tested for particulates on the Production rig (Section 2.1.3). The extraction method was the modified method Section 2.3.1.

The conditions of the tests are outlined in detail in Appendix A. In summary HFE-71DE was flushed through for 5 minutes in two directions at 1.0 l/min. HFE-7100 was then flushed through for 5 minutes at 1.1-1.2 l/min in both directions, followed by a final rinse with clean HFE-7100 at 0.6 l/min.

Table 14 lists the results for the 1/2″ stainless steel pipe

Table 14 - Results for 1/2" Stainless Steel Pipe

Trial No.	Pipe Description	Internal Surface Area	Test Description	No. of particles 25-50 micron	50-100 micron	100 -175 micron	>175 micron
			Target	unlimited	5	1	0
3	1/2″ Stainless steel 2 metre	0.77 sqft	100 ml G93	1	0	0	2
			F303	5	2	0	2
			Blank	7	0	0	0
4	1/2″ Stainless steel 2 metre	0.77 sqft	100 ml G93	4	2	0	0
			F303	0	0	0	0
			Blank	2	0	0	0
5	1/2″ Stainless steel 2 metre	0.77 sqft	100 ml G93	3	1	0	0
			F303	11	3	1	1
			Blank	8	1	0	0

From the results in Table 14 it is evident that the procedures and equipment can meet the RAAF's particle specification for 1/2″ pipes. However, larger particles were found on two occasions. In Trial 3 two large particles were found and identified as copper. These were found to be coming from a connection on the Production rig and were carried over from the previously tested copper pipe. One end of the previous copper pipe was found to be deformed which resulted in additional particle generation at this connection.

When the connections were re-cleaned, the copper particles were not observed again. This demonstrates the importance of the white inspection membrane at the end of the final flush. In field use, the presence of such particles should alert operators to a problem and result in reinspection and cleaning of the cleaning rigs and connections.

In Trial 5 the more exacting F303 particle extraction method resulted in one larger particle found. The specification the RAAF use is based on the G93 method and the F303 is much more stringent than the requirements in G93. Trial 5 listed in Table 14 met the RAAF specification when the G93 method was used. Consequently it is acceptable, but does demonstrate the importance of the final inspection of the membrane in the final flush procedures.

4. Discussion

4.1 Delivery Vessel Pressure and Flowrates

The pipe cleaning trials have been performed over a range of pipe diameters, materials and fittings and have been shown to meet the RAAF's cleanliness specifications for particulate and NVR. However, unlike traditional systems that rely on a pump, pressure systems depend on the initial pressure and the internal diameter and restrictions within the pipes to determine the final flow rate of the solvents through he pipes. Table 15 and 16 lists the supply pressures used during the trials for the recirculating used HFE-71DE and HFE-7100, respectively for all of the pipe internal diameters tested. Table 17 lists the pressures and flowrates in the Final Rinse vessels. Also included is the calculated flow rate required for the onset of turbulent flow, taken to be when the Reynolds number reaches 4000.

Table 15 - Pressure Used and Flowrates Achieved for HFE-71DE Recirculating Solvent

Pipe description	ID (mm)	Supply vessel pressure (KPa)	flowrate range (ml/min)	Turbulent flow rate onset HFE-71DE (ml/min)
1/2" SS	10.3	100	970-1110	612
3/8" Copper	7.24	100	830-980	435
5/16" P3	6.9	100	930-1080	423
5/16" FA-18	6.17	100	960-1030	385
1/8" HS-748	3.0	500	980-1540	183

Table 16 – Pressures Used and Flowrates Achieved for the HFE-7100 Recirculating Solvent

Pipe description	ID (mm)	Supply vessel pressure (KPa)	flowrate range (ml/min)	Turbulent flow rate onset HFE-7100 (ml/min)
1/2" SS	10.3	100	1100-1200	750
3/8" Copper	7.24	100	680-770	532
5/16" P3	6.9	100	720-850	516
5/16" FA-18	6.17	150-160	1010-1070	468
1/8" HS-748	3.0	500	1060-1310	225

Table 17 - Pressures Used and Flowrates Achieved for the Unused Final Rinse Solvent

Pipe description	ID (mm)	Supply vessel pressure (KPa)	flowrate range (ml/min)	Tubulent flow rate onset HFE-7100 (ml/min)
1/2" SS	10.3	200-210	620-650	750
3/8" Copper	7.24	200	650-700	532
5/16" P3	6.9	350	650-800	516
5/16" FA-18	6.17	220-240	600	468
1/8" HS-748	3.0	350	670-690	225

Final rinse pressures are generally higher than those required for the recirculation rigs due to the backpressure through the membrane filter positioned at the end of the pipe that acts as an inspection aid.

What is shown by Tables 15 through 17 is the pressure vessel delivery method is capable of achieving the turbulent flowrates required for pipe diameters ranging from 1/8" to 1/2" and should be suitable for all pipe systems the RAAF must maintain. However, for 1/2" pipes the final flush supply pressure could be increased to ensure the turbulent threshold is achieved.

4.2 Non-Volatile Residue Removal

The pipe cleaning method tested here appears to readily achieve the RAAF NVR specifications. It was tested twice. First with 1/4" stainless steel pipes and then with P3 pipes. In both occasions the NVR achieved was well within specifications.

Using 1/4" pipes and the proof of concept rig it was shown that HFE-7100 on its own was capable of removing "Krytox", the most likely oxygen system contaminant, and "Aeroshell" grease. In addition the more difficult to clean, OM-15, was effectively removed to RAAF specifications with the addition of only 600 ml of HFE-71DE.

For the P3 pipes it was shown that using the used HFE-71DE and HFE-7100 solvents in the recirculating rigs, without the final flush with clean HFE-7100, was sufficient to achieve the NVR specification for "Aeroshell" grease and OM-15 at the conditions tested.

It is possible that the RAAF NVR specifications could be achieved without the need to perform the final flush with clean HFE-7100. However, there is currently no in-field monitoring test to determine the accumulating NVR in the recirculating solvents, and these levels of NVR will no doubt eventually rise until the cleaning performance is compromised. It was shown in the P3 pipe tests that the NVR limit for the cleaned pipe could be achieved with NVR contamination in HFE-71DE and HFE-7100 of 124 and 9 mg/l, respectively. However, in the field this could accumulate to higher levels.

Laboratory work is continuing to determine the NVR levels that are accumulating in the field solvents and in developing in-field tests to determine the NVR accumulation in the HFE recirculating solvents. The aim is to eventually set an upper 'in-field' limit for NVR in the recirculating HFE solvents, an inspection interval of the recirculating solvents and advise on an in-field NVR test method.

It is recommended that until this is finalised the final flush be continued, to give a high level of confidence in the cleaning procedures and equipment.

4.3 Particulate Removal

The particulates were tested for pipe sizes ranging from 1/8" to 1/2" and covered the three major material types, and a number of different pipe connections. In all cases it was shown that the equipment and procedures could meet the RAAF participle specification so long as care was taken to limit the particle generation experienced during the connection of pipes and fittings.

Particle generation during the connection of pipes was found to be a substantial limitation in achieving the particle specification and just one reconnection of a pipe can generate enough additional particles in the wetted pipe areas to exceed the RAAF's particle specification.

In general, the concept that turbulent flow of the high density solvents can dislodge and suspend particulates sufficiently to remove them from the internal surfaces of pipes has been proved. The stronger solvent, HFE-71DE, is also capable of removing any oily or greasy substances that may be binding particulates and improves the particulate removal.

It was found that flushing for 5 minutes in each direction was sufficient to achieve the RAAF cleanliness specifications. In addition, there was no observable difference when flowrates were increased by increasing the pressure in the delivery vessel. An initial high velocity nitrogen blowdown of the pipes was found to not have any noticeable affect on the results.

Also, all tests were carried out by attempting to keep the test pipes as horizontal as possible during the recirculating stages and were placed in a downward plane during the final rinse to gain maximum gravity assistance in the removal of heavy particulates. It is suggested that this configuration be continued.

4.4 Lessons Learnt

During the course of the various pipe cleaning tests a number of additional observations have been made that have an impact on the efficiency of the pipe cleaning process. The major observations are listed below.

1. Stainless steel braided flexible hose can be a source of trapped particles in the SS braid. Care should be taken when using such hoses so that the braid is never cleaned in a way that trapped external particles can be in contact with the end of the braided hose and get in the wetted areas. It is also recommended that SS flexible hose only be used where necessary.

2. As well as particle generation that can occur when reconnecting pipes, the stainless steel filter holder at the end of the final rinse rig can also cause some initial particle contamination when first connected. Therefore, initial particles on the membrane are not a cause of rejection, unless they continue to occur in subsequent final rinses.

3. The possibility of a one off failure to clean, as demonstrated in the 1/2" pipe trials, demonstrates the value of having the white inspection membrane at the end of the final flush rig.

4. Newly manufactured stainless steel pipe have a substantial particle contamination that requires a more vigorous gross clean. It is recommended with new SS pipes that a solvent wetted pull through always be used before cleaning on the pipe cleaning rig. The pull through should be repeated until the lint free cloth shows no visible contamination.

5. There is a potential for poorly machined pipe ends to cause carry over of particulates in the pipe cleaning rig connections. It is recommended that only quality pipes and fittings be attached to the cleaning rigs. If such contamination occurs the rigs connectors need to be very carefully cleaned.

6. The cleaning rig is made from stainless steel and can take a while to initially clean up and remove its own particulate contamination before use. Any contamination in the rig and fittings within the rig will have a negative impact on the cleaning performance. Care should be taken to always ensure that the equipment is cleaned to the same standards as the oxygen system pipes and components being cleaned.

7. To avoid the possibility of prematurely clogging in-line filters on the pipe clean rig and slowing the flowrate appreciable, the cleaning solvents should be filtered before use.

4.5 Future Directions

The issue of NVR accumulation in the recirculating solvent and the affect that has on resultant cleaning performance is still not fully understood. This is important to fully understand as HFE solvents are expensive and premature quarantining of these solvents would add considerably to the cost of the procedure. Alternatively, using

these solvents beyond their effective life could have serious implications for aircraft oxygen system safety. Further work is required to determine:

1. the maximum amount of NVR that can be tolerated in the recirculating HFE solvents before they fail to meet the required surface NVR cleanliness level of the cleaned pipes,
2. the recommended analysis intervals for the solvents in the recirculating vessels,
3. an effective and safe in-field analytical test to determine the NVR levels in the HFE solvents.

Also, particle generation that can occur when pipes are connected has been shown to significantly contribute to particle contamination levels in the cleaned pipes. Further research should be undertaken to determine what pipe-fitting combinations produce the least amount of particulate contamination when undone and refastened, and which pipe fitting types and materials should be avoided.

5. Conclusion

The trial of the pipes on the various trial rigs showed that the procedure can achieve the cleanliness requirements, once particle generation that can occur during pipe reconnection is taken into consideration. For stainless steel pipes, a pull through is recommended as a precleaning stage. Testing of the pipe cleaning rigs shows that 5 minutes in each direction with recirculating HFE-71DE and HFE-7100 at flowrates above turbulent flowrates, followed by a final rinse with unused HFE-7100 is sufficient to achieve the RAAF specifications with a high degree of confidence.

6. References

1. Steinberg, T. A., Newton, B. E. and Beeson, H. D. (Eds), Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Tenth Volume, ASTM STP 1454, West Conshohocken, PA, USA, 2003.

2. ASTM Method G93-96 Standard Practice for Cleaning Methods and Cleanliness Levels for Material and Equipment used in Oxygen-Enriched Environments, ASTM, West Conshohocken, PA, USA.

3. SAE ARP 1176 Aerospace Recommended Practice – Oxygen System and Component Cleaning and Packaging.

4. Mil-Std-1246C Product Cleanliness Levels and Contamination Control Program.

5. AMPTS Technical Report, RAAF Oxygen System Cleaner Replacement Report, AMPTS/4301/07/03 Pt6(70), RAAF Laverton Australia, 1999.

6. AAP 7055.001-99 Australian Air Publication: Liquid and Gaseous Dry Breathing Oxygen Maintenance Instructions, RAAF, AMPTS (DAIRMAINT).

7. Perry, R. H and Green, D. W., Perry's Chemical Engineers' Handbook, 7th Ed., McGraw-Hill, 1998.

8. ASTM Method F303-89 Standard Practice for Sampling Aerospace fluids from Components, ASTM, West Conshohocken, PA, USA.

9. ASTM Method F331-00 Standard Test Method for Non-volatile Residue of Solvent Extract from Aerospace Components (Using Rotary Flash Evaporator), ASTM, West Conshohocken, PA, USA.

10. ASTM Method F312-97 Standard Test Method for Microscopal Sizing and Counting Particles from Aerospace Fluids on Membrane Filters, ASTM, West Conshohocken, PA, USA.

11. Fletcher, L. E., Zugno, R. and Dimas, J., *Pipe Cleaning using HFE Solvents and Assessment of Particle Contamination Found During Pipe Connection,* In Steinberg, T. A., Newton, B. E. and Beeson, H. D. (Eds), Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Tenth Volume, ASTM STP 1454, West Conshohocken, PA, USA, 2003.

Appendix A: Description of Test Conditions for Pipe Trials

Table 18 - Test conditions for HS748 pipes, original verification method.

Trial Number	Pipe Description	HFE-71DE P1 Direction Pressure (KPa)	HFE-71DE P1 Direction Flowrate (l/min)	HFE-71DE P1 Direction Total time (min:sec)	HFE-71DE P2 Direction Pressure (KPa)	HFE-71DE P2 Direction Flowrate (l/min)	HFE-71DE P2 Direction Total time (min:sec)	HFE-7100 P1 Direction Pressure (KPa)	HFE-7100 P1 Direction Flowrate (l/min)	HFE-7100 P1 Direction Total time (min:sec)	HFE-7100 P2 Direction Pressure (KPa)	HFE-7100 P2 Direction Flowrate (l/min)	HFE-7100 P2 Direction Total time (min:sec)	Final Rinse P1 Direction Pressure (KPa)	Final Rinse P1 Direction Flowrate (l/min)	Final Rinse P1 Direction Total time (min:sec)
1	5 old 748 pipes	350	0.95	16:55	350	0.87	23:00	550	0.75	20:20	550	0.72	20:40	500	1.15	0:47
2	5 old 748 pipes	500	1.21	18:06	500	1.28	16:47	500	1.09	20:07	500	1.10	19:46	200	0.64	1:30
All 5 pipes had 300ul particles added																
3	5 old 748 pipes	500	1.17	17:52	500	1.17	17:56	500	1.02	20:45	500	0.99	21:02	200	0.65	1:27
All 5 pipes had 300ul particles added, pipes shaken throughout recirc stages																
4	5 old 748 pipes	500	0.99	15:11	500	0.98	15:07	500	0.77	16:29	500	0.73	17:21	200	0.66	1:31
Found a lot of metallic particles and pipe ends showed major gouging. ISO pipe connectors replaced with BSPP connectors for this trial																
5	5 old 748 pipes	500	1.31	16:32	500	1.31	16:30	500	1.19	15:57	500	1.2	15:28	500	1.16	0:49
All 5 pipes had 300ul particles added, all connections and pipe ends cleaned including braided hose, which seemed to trap particles. Braided hose removed from final rinse here after																
6	5 old 748 pipes	500	1.34	16:12	500	1.34	15:10	500	1.19	16:48	500	1.18	16:44	200	055	1:25
No particles added to this trial.																
7	5 old 748 pipes	500	1.32	15:09	500	1.31	15:35	500	1.17	18:40	500	1.17	18:40	200	0.64	1:30
Flow direction switched half way through recirc in an attempt to better dislodge particles. Tapping of connections to help suspend particles to be done for one minute after each switch																
8	2 old 748 pipes	500	1.7	15:16	500	1.7	15:08	500	1.48	19:20	500	1.5	19:00	200	0.82	1:10
No ganging of pipes used and difference in pipe elevation kept to 9.5cm																
11	2 old 748 pipes	500	1.41	16:47	500	1.54	16:24	500	1.23	24:26	500	1.24	24:05	200	1.11	0.51
300ul particles added to each pipe. 8 micron filter placed in between two pipes and reversed with each flow change																
15	5 old 748 pipes	500	1.07	13:02	500	1.20	11:01	500	1.05	13:39	500	1.04	13:35	80	0.32	2:56
300ul particles added to each pipe. Boeing conversion fittings used																

Table 19 - Test Descriptions for HS-748 tests, modified verification method.

Trial Number	Pipe Description	HFE-71DE P1 Direction			HFE-71DE P2 Direction			HFE-7100 P1 Direction			HFE-7100 P2 Direction			Final Rinse P1 Direction		
		Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)
16	2x no 99 2x no 100	500	1.28	15:00	500	1.27	15:20	500	1.06	20:28	500	1.08	19:50	100	0.70	1:23
Dirtied with 300ul particles in each pipe, N2 purge for 2 minutes. End fittings washed with filtered 7100, connected using pirtek ss fittings and bspp unions ex east sale																
17	2x no 99 2x no 100	500	1.38	18:16	500	1.42	17:38	500	1.25	21:41	500	1.25	21:39	200	0.51	1:50
Dirtied with 300ul particles in each pipe, N2 purge for 2 minutes. End fittings washed with filtered 7100, connected using pirtek ss fittings and bspp unions ex east sale																
18	2x no 99 2x no 100	500	1.43	17:07	500	1.43	17:01	500	1.26	21:26	500	1.26	21:12	200	0.52	1:47
Dirtied with 300ul particles in each pipe, N2 purge for 2 minutes. End fittings washed with filtered 7100, connected using pirtek ss fittings and bspp unions ex east sale																
19	2x no 99 2x no 100	500	1.45	5:10	500	1.50	5:00	500	1.25	5:10	500	1.29	5:00	200	0.52	1:50
Dirtied with 300ul particles in each pipe, N2 purge for 2 minutes. End fittings washed with filtered 7100, connected using pirtek ss fittings and bspp unions ex east sale																
20	2x no 99 2x no 100	500	1.42	5:10	500	1.46	5:00	500	1.27	5:10	500	1.31	5:00	200	0.50	2:00
Dirtied with 300ul particles in each pipe, no N2 purge. End fittings washed with filtered 7100, connected using pirtek ss fittings and bspp unions ex east sale																
21	2x no 99 2x no 100	500	1.40	16:03	500	1.40	15:50	500	1.28	15:37	500	1.25	16:14	250	0.54	1:50
Dirtied with 300ul particles in each pipe, no N2 purge. End fittings washed with filtered 7100, connected using pirtek ss fittings and bspp unions ex east sale																
22	2x no 99 2x no 100	500	1.40	5:05	500	1.40	5:05	500	1.25	5:05	500	1.24	5:05	350	0.69	1:27
Dirtied with 300ul particles in each pipe, no N2 purge. Same fittings as above with pipe shaking for last 30 secs in each direction																
23	2x no 99 2x no 100	500	1.43	5:05	500	1.43	5:05	500	1.28	5:05	500	1.27	5:05	350	0.67	1:30
Dirtied with 300ul particles in each pipe, no N2 purge. Same fittings as above with pipe shaking for last 30 secs in each direction																
24	2x no 99 2x no 100	500	1.35	15:04	500	1.37	14:39	500	1.21	16:32	500	1.20	16:37	350	0.69	1.27
Dirtied with 300ul particles in each pipe, no N2 purge. Same fittings as above																

Table 20 - Test Conditions for FA-18 trials

Trial Number	Pipe Description	HFE-71DE P1 Direction Pressure (KPa)	HFE-71DE P1 Direction Flowrate (l/min)	HFE-71DE P1 Direction Total time (min:sec)	HFE-71DE P2 Direction Pressure (KPa)	HFE-71DE P2 Direction Flowrate (l/min)	HFE-71DE P2 Direction Total time (min:sec)	HFE-7100 P1 Direction Pressure (KPa)	HFE-7100 P1 Direction Flowrate (l/min)	HFE-7100 P1 Direction Total time (min:sec)	HFE-7100 P2 Direction Pressure (KPa)	HFE-7100 P2 Direction Flowrate (l/min)	HFE-7100 P2 Direction Total time (min:sec)	Final Rinse P1 Direction Pressure (KPa)	Final Rinse P1 Direction Flowrate (l/min)	Final Rinse P1 Direction Total time (min:sec)
6	11 x 5/16" FA-18 pipe	100	1.03	5:10	100	0.96	5:30	150	1.01	5:15	150	1.03	5:30	220	0.60	1:40
Dirtied with 1200ul particles, 600ul in each end																
7	11 x 5/16" FA-18 pipe	100	1.03	5:15	100	0.99	5:30	160	1.01	5:30	160	1.07	5:15	240	0.60	1:35
Dirtied with 1200ul particles, 600ul in each end																

Table 21 - Test Conditions P3 pipe trials.

Trial Number	Pipe Description	HFE-71DE P1 Direction Pressure (KPa)	HFE-71DE P1 Direction Flowrate (l/min)	HFE-71DE P1 Direction Total time (min:sec)	HFE-71DE P2 Direction Pressure (KPa)	HFE-71DE P2 Direction Flowrate (l/min)	HFE-71DE P2 Direction Total time (min:sec)	HFE-7100 P1 Direction Pressure (KPa)	HFE-7100 P1 Direction Flowrate (l/min)	HFE-7100 P1 Direction Total time (min:sec)	HFE-7100 P2 Direction Pressure (KPa)	HFE-7100 P2 Direction Flowrate (l/min)	HFE-7100 P2 Direction Total time (min:sec)	Final Rinse P1 Direction Pressure (KPa)	Final Rinse P1 Direction Flowrate (l/min)	Final Rinse P1 Direction Total time (min:sec)
26	P3 Pipe No 1,2, 3	100	0.95	5:00	100	0.93	5:00	100	0.78	5:10	100	0.73	5:15	250	0.6	1:36
Hand wipe of connections cleaned as received 5min in each direction																
27	P3 Pipe No 1,2,3	100	1.00	5:05	100	0.99	5:00	100	0.72	5:05	100	0.67	5:10			
25mg om15 added no final rinse																
28	P3 Pipe No 1,2,3	100	1.05	5:05	100	0.97	5:15	100	0.74	5:10	100	0.70	5:15			
25mg om15 added no final rinse																
29	P3 Pipe No 1,2,3	100	0.61	5:05	100	0.56	5:20	100	0.55	5:10	100	0.48	7:00			
25mg grease added no final rinse																
30	P3 Pipe No 1,2,3	100	1.18	5:00	100	1.30	5:37	100	0.83	5:05	100	0.72	5:22	350	0.65	1:30
Hand wipe 1200ul part added 5min in each direction																
31	P3 Pipe No 1,2,3	100	1.10	15:00	100	1.11	15:00	100	0.80	15:00	100	0.85	15:00	350	0.8	1:25
Hand wipe 1200ul part added 15 min in each direction																
32	P3 Pipe No 1,2,3	300	2.27	4:55	300	2.27	4:55	300	1.89	5:00	300	1.84	5:00	350	0.67	1:30
Hand wipe 1200ul part added 5 min in each direction																
33	P3 Pipe No 1,2,3	500	3.55	5:00	500	3.72	5:00	500	2.84	5:00	500	2.83	5:00	350	0.67	1:30
Hand wipe 1200ul part added 5 min in each direction																
34	P3 Pipe No 3,4,5	100	1.08	5:00	100	1.05	5:00	100	0.75	5:00	100	0.73	5:10	350	0.67	1.25
New pipes 4 and 5 cleaned as received hand wiped cleaned 5 min in each direction pipes 4 and 5 specialist cleaned																
35	P3 Pipe No 3,6,7	100	1.05	5:05	100	1.02	5:05	100	0.75	5:00	100	0.72	5:00	350	0.67	1:30
Cloth pull through on pipes 6 and 7 x2 then hand wiped and cleaned 5 min in each direction pipes 6 and 7 not specialist cleaned																
36	P3 Pipe No 3,8,9	100	1.05	5:05	100	1.05	5:05	100	0.8	5:05	100	0.77	5:05	350	0.67	1:30
Cloth pull through on pipes 8 and 9 x3 then hand wiped and cleaned 5 min in each direction pipes 8 and 9 not specialist cleaned																

Table 22 - Test Conditions 3/8" Copper pipe trials.

Trial Number	Pipe Description	HFE-71DE P1 Direction			HFE-71DE P2 Direction			HFE-7100 P1 Direction			HFE-7100 P2 Direction			Final Rinse P1 Direction		
		Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)
1	1x 4m 3/8" copper pipe	100	0.92	4:30	100	0.83	5:00	100	0.77	5:03	100	0.70	5:30	200	0.65	1:30
Dirtied with 1200ul of particles 600ul in each end																
2	1x 4m 3/8" copper pipe	100	0.95	5:20	100	0.98	5:30	100	0.75	5:01	100	0.68	5:30	200	0.70	1:25
Dirtied with 1200ul of particles 600ul in each end																

Table 23 - Test Conditions 1/2" Stainless steel pipe trials.

Trial Number	Pipe Description	HFE-71DE P1 Direction			HFE-71DE P2 Direction			HFE-7100 P1 Direction			HFE-7100 P2 Direction			Final Rinse P1 Direction		
		Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)	Pressure (KPa)	Flowrate (l/min)	Total time (min:sec)
3	1 x 2.22m ½" SS pipe	100	1.09	5:00	100	0.97	5:00	150	1.21	5:00	150	1.20	5:00	210	0.65	1:25
Pipe tested in original condition																
4	1 x 2.22m ½" SS pipe	100	1.05	5:05	100	0.97	5:30	100	1.20	5:05	100	1.18	5:30	210	0.65	1:25
Dirtied with 1200ul particles, 600ul in each end																
5	1 x 2.22m ½" SS pipe	100	1.11	5:00	100	1.04	5:30	100	1.11	5:00	100	1.14	5:30	200	0.62	1:35
Dirtied with 1200ul particles, 600ul in each end																

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Oxygen System Pipe Cleaning System

Lyn E. Fletcher, Robert Zugno and Jim Dimas

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19. ABSTRACT
This report details the stages in the development of a novel oxygen system pipe cleaning system, and associated cleaning procedures, for use at RAAF oxygen maintenance workshops. This cleaning system uses 3M HFE solvents and pressure vessels for solvent delivery. Detailed test results and procedures are included. These tests covered RAAF oxygen system pipes in various diameters ranging from 1/8" to 1/2" in stainless steel, copper and aluminium, and various pipe connectors. The tests showed that the final system developed is able to meet the RAAF cleanliness specification for oxygen systems for both non-volatile residue and particulate contamination.

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